

Wearable Technology for Bio-Chemical Analysis of Body Fluids During Exercise

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Abstract—This paper details the development of a textile based fluid handling system with integrated wireless biochemical sensors. Such research represents a new advancement in the area of wearable technologies. The system contains pH, sodium and conductivity sensors. It has been demonstrated during on-body trials that the pH sensor has close agreement with measurements obtained using a reference pH probe. Initial investigations into the sodium and conductivity sensors have shown their suitability for integration into the wearable system. It is thought that applications exist in personal health and sports performance and training.

I. INTRODUCTION

TO date the majority of research in the area of wearable sensors has focused on the development of devices which measure physical parameters such as motion, respiration and heart rate [1]-[3]. However, textiles are often employed in sports applications to capture body fluids and wick them away from the skin surface. Such fabrics can be used as a platform for the development of biochemical sensors used to monitor the changing composition of fluids such as sweat under stress or exercise.

Sweat is a clear hypotonic odorless fluid often described as an ultrafiltrate of plasma. Its major constituents are sodium, potassium, calcium, magnesium and chloride [4]. It is easily accessible with the sweat rate in human males during exercise measured in the region of $0.85 \text{ mg cm}^{-2} \text{ min}^{-1}$ for the lower back.

Changes in the composition of sweat can be used to provide information on a person's physiological condition [5]. In addition, prolonged exercise can lead to dehydration and a change in the electrolyte concentrations in sweat. For elite athletes, a visible reduction in performance will occur for a 2 % drop in body weight due to dehydration. Further fluid loss can lead to symptoms such as irritability, headache, dizziness, cramps, vomiting, increased body temperature and heart rate, increased perceived work rate, reduced mental function, slower gastric emptying [6].

Manuscript received February 1, 2008. This work was supported by the Australian Research Council International Linkage Program, European Union (Biotex) under Grant FP6-2004-IST-NMP-2 and Science Foundation Ireland under Grant SFI 03/IN.3/I361.

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On the other hand drinking too much water can lead to hyponatremia, which is characterized by low levels of sodium. This results in symptoms such as headache, nausea, vomiting and muscle cramps. When there is a quick onset of hyponatremia, for example during prolonged exercise, it can lead to more severe complications such as seizures, coma, brain damage and death [7].

Therefore, it can be seen that real-time knowledge of the variation in sweat composition during exercise can be useful in developing individualized rehydration strategies to maximize performance in elite athletes and to protect amateur sports people from developing potentially fatal conditions.

In addition to monitoring the electrolyte balance, knowledge of sweat pH can be useful. It has been shown that sweat pH during exercise will change with the onset of metabolic alkalosis [8]. Therefore, pH measurements may also provide a non-invasive method of relating the build-up of acid in muscle cells during exercise.

BIOTEX (Bio-sensing textile for health management, see www.biotex-eu.com) is an EU funded project aiming to develop dedicated biochemical-sensing techniques to monitor body fluids via sensors distributed on a textile substrate. Initial applications are envisaged for personal health and sports performance and training.

A textile based platform has been developed for the capture and delivery of sweat samples produced during exercise. On the sample delivery platform, a colorimetric pH sensor was fabricated directly onto the textile for the measurement of sweat pH. The sensor has been shown to be successful in real-time monitoring of sweat composition during exercise trials. Work on the integration and testing of sodium and conductivity sensors on the fabric channel is also reported.

II. EXPERIMENTAL PROCEDURE

A. Fluid Handling System

To obtain a real-time biochemical analysis of sweat, a method of sample collection, delivery to the sensor site and removal must be developed. For wearable sensors, such a fluid handling system can be achieved through the use of textiles with inherent moisture wicking properties via capillary action. A fabric patch is prepared such that it

collects sweat from the skin surface and moves it through a predefined channel to the sensing area. A commercial polyimide/lycra® blend, supplied by Sofileta (www.sofileta.com), which is commonly utilized in sportswear, has been chosen for this purpose.

There are large variations in sweat rate and constituent concentrations over the skin surface [9]. Therefore, it is necessary to place the patch in the same location each time. The upper body is preferred for ease of access and areas of high sweat rate include the forehead, chest, scapula, hands and lower back. Of these the latter is preferred as the patch can be integrated into a belt worn during exercise.

The patch covers an area of 55 x 40 mm². A fluidic channel measuring 7 x 20 mm² at the sensor area and 2 x 20 mm² at its end is defined by screen-printing an acrylic hydrophobic paste on either side of the fabric. These dimensions were chosen to match the average sweat rate at the lower back.

Following this, a polyurethane film is affixed to the back or skin-side of the patch, leaving an area measuring 7 x 8 mm² at the top of the channel exposed. This is the inlet through which sweat enters the fluid handling system.

An acquisition layer is placed on the skin side of the patch to maximize the sample collection area. It transports sweat to the inlet where it enters the fluidic channel and comes into contact with the pH, sodium and conductivity sensors. The channel dimensions and sensor positions are shown in Fig. 1.

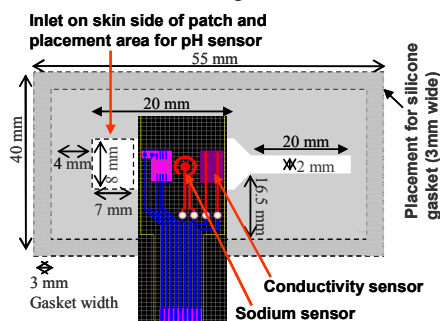


Fig. 1. Layout of fluid handling system and position of pH, sodium and conductivity sensors.

When the fluid reaches the end of the channel it is stored using a super absorbent (SAB) material, which acts to continuously draw fresh sweat from the skin surface to provide a passive pumping action. The absorbent (Absortex) is supplied by Smartex (www.smartex.ie) and has a free swell capacity of 25 g/g and a basis weight of 172 g/m². To obtain 2 hours operation at an average sweat rate of 17 mg/min, for the lower back [9], the pump must be able to collect 2 g of sweat. Therefore, 80 mg of Absortex is required, which is equivalent to 4.65 cm² or a space measuring 15 x 30 mm² at the end of the channel.

A silicone gasket is placed around the fabric patch. This is used to mount the cover containing the LEDs for the pH sensor as described in section II B. It also serves to block any ambient light.

B. pH Sensor

The pH sensor is positioned as shown in Fig.1 and is based on the use of a pH sensitive dye, which varies in colour depending on the acid/base nature of the sweat moving along fluidic channel. Since human sweat generally lies in the region of pH 5 – 7 [10], bromocresol purple (BCP, pKa = 6.2) has been chosen as it will show a colour change from yellow to blue over this range of measurement. It is fabricated directly onto the fabric channel by co-immobilising the dye with tetraoctyl ammonium bromide.

To obtain quantitative pH measurements a paired emitter-detector LED configuration was used [11]. These LED's (Kingbright, L934SRCG) are used to measure the pH dependent (blue) colour intensity of the dye and are held over the fabric channel using a black PMMA cover which is positioned using the rubber gasket. The sensor and optical system is illustrated in Fig. 2.

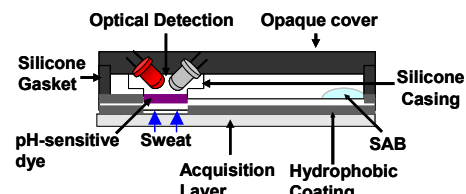


Fig. 2. Illustration of pH sensor and optical detection system

The detector is reverse-biased at +5 V, which charges the capacitance across it. This is discharged by the photocurrent generated upon incident light. The discharge rate is proportional to the intensity of the light reaching the detector. A digital output can be obtained by using a basic detection/timer circuit which measures the time it takes the photocurrent to discharge the voltage from +5 V (logic 1) to +1.7 V (logic 0). This is done using a Crossbow Mica2dot Mote with the data being wirelessly transmitted to a Mica2 base station connected to a laptop for analysis.

C. Sodium and Conductivity Sensor

The sodium sensor has been developed by CEA-Leti (www-leti.cea.fr). It is fabricated on a flexible kapton surface and consists of a gold reference electrode and a solid contact ion selective electrode (SC-ISE). This is formed from a gold layer covered with a polymeric membrane, the potential of which is a function of the sodium concentration. In this case the polymer used is polypyrrole. This conducting polymer has been used successfully since the early 1990's for solid contact ISE's. Other commonly used polymers include aniline and thiophene. The doping material, which confers conductivity on the polymer, may also be changed allowing greater scope for optimizing sensor performance [12], [13].

The conductivity sensor has been developed by the University of Pisa and is also fabricated on a kapton surface. It is designed to have a range of 1 – 30 mS and works on the principle of measuring AC resistance.

The electrical conductance of sweat is a function of variables such as the species and concentrations of ions

present, temperature and geometry of the conductivity cell. When the latter two are held constant it is possible to obtain a global picture of the type and concentration of ions present.

Data from these sensors can be measured in real-time using a control system developed by CSEM (www.csem.ch). The device has specifically been designed to interface with all the sensors developed as part of the BIOTEX project and future work will consist of interfacing the pH sensor with this system. It contains a graphical touch screen display, a removable memory-stick for data storage and transfer and bluetooth communication for short-range data streaming or data download. An image of the integrated system and a magnified image of the kapton patch is shown in Fig. 3.

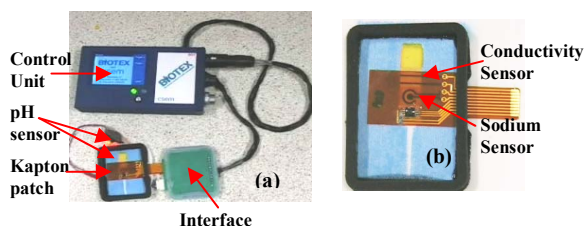


Fig. 3. Image of (a) pH, conductivity and sodium sensor integrated with CSEM electronics and (b) magnified image of pump and kapton patch

D. Reference Methods

To validate the measurements obtained by the pH sensor a commercially available on-skin pH meter, skincheck1™ (www.hannainst.co.uk), is used. This is placed in contact with the surface of a reference patch, which is fabricated as described in section II A except with channel dimensions of 15 x 15 mm² at the inlet. The increased size is designed to accommodate the skincheck™ pH meter. Measurements are taken at 5 minute intervals and readings compared to those obtained from the developed pH sensor.

In the case of the sodium sensor, a reference sodium ISE has been developed in house. All chemicals were supplied by Sigma and analytical grade. Potentiometric ISE membranes were prepared using 250 mg 2-Nitrophenyl octyl ether, 125 mg PVC, 6.5 mmol kg⁻¹ 4-tert-Butylcalix[4]arenetetraacetic acid tetraethyl ester (Sigma 420484) and 2.7 mmol kg⁻¹ potassium tetrakis(4-chlorophenyl) borate dissolved in dry THF and evaporated slowly [14], [15]. Membranes were conditioned in 0.1 M sodium chloride for 12 hours and deionised water for half an hour prior to ISE titrations. Calibration was carried out using strips of polyimide/lycra® fabric soaked in NaCl solutions of known concentration, to which the electrodes were applied. Calibrations of the reference ISE were performed before and after a trial to ensure the electrode was in good working order.

E. Experimental Procedure

A purposely designed waistband has been fabricated by Smartex for use in on-body trials. It houses the pH sensor, sensor electronics and reference patch. The pH sensor is completely enclosed by the waistband, while there is an opening to the reference patch. This patch is also used to

obtain reference measurements for the sodium sensor. An image of the waistband placed on a subject during trials is shown in Fig. 4.

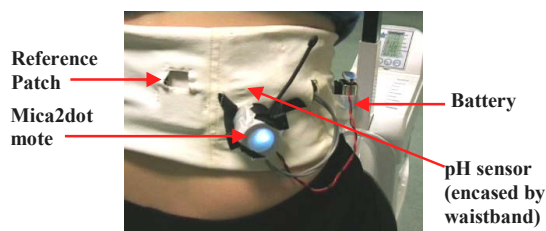


Fig. 4. Arrangement of sensor and reference patch in waistband

The operation of the pH and reference sodium sensors was evaluated in separate trials. Both male and female subjects were studied. At the present stage subjects are not subjected to any dietary or environmental controls prior to trials.

In each case, the subject is asked to cycle at a pace which is self-selected for a period between 30 and 60 minutes. It is generally observed that sweating will commence 10 – 15 minutes after exercise begins. However, as the fabric patch cannot be observed, no measurements were taken until 30 minutes of exercise had elapsed. This ensured that the passive pump was fully wetted.

In the case of the sodium and conductivity sensors, calibration curves have been obtained by placing the patch in solutions of 0.02, 0.04, 0.06 and 0.08 M Na⁺. In each case 20 minutes was allowed for stabilization. The results were recorded in real-time using the CSEM control unit.

III. RESULTS

Typical results obtained for the pH sensor during on body trials is shown in Fig. 5. It can be seen that there is good agreement (to within 0.2 pH) between the sensor and reference measurements.

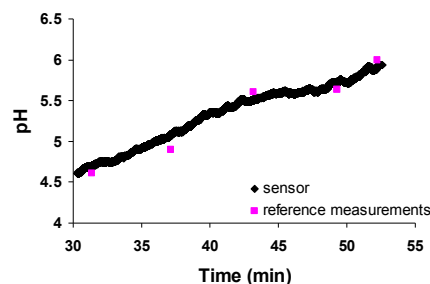


Fig. 5. Typical results obtained for pH sensor during on-body trials.

The above experiment was repeated for three male subjects and the results are shown in Fig. 6. It can be seen that the sensor output is stable and reproducible with a maximum standard deviation of ± 0.321 . Differences are expected as sweat rates vary widely and are influenced by factors such as body size, gender, metabolism, exercise intensity and environmental conditions [16].

Trial results are also shown for the sodium sensor developed for use as a reference method in Fig. 7. Results fall within the literature range, but for the current subject appears to be near the upper range.

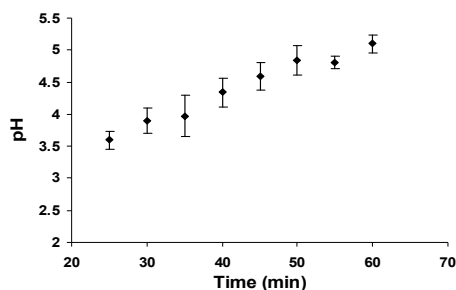


Fig. 6. Reproducibility of pH sensor during on-body trials

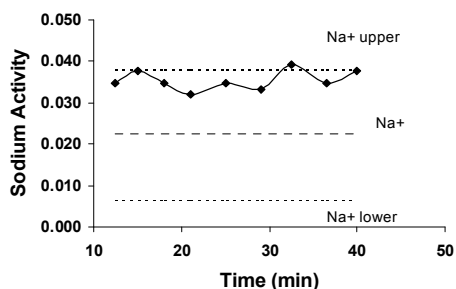


Fig. 7. Na^+ data collected during exercise trial. Literature typical average, upper and lower limits of sodium in sweat are also shown.

Work on the integration and testing of the sodium and conductivity sensors developed by CEA-Leti and University of Pisa are presented. Initial calibration curves obtained using the CSEM control unit is shown in Fig. 8.

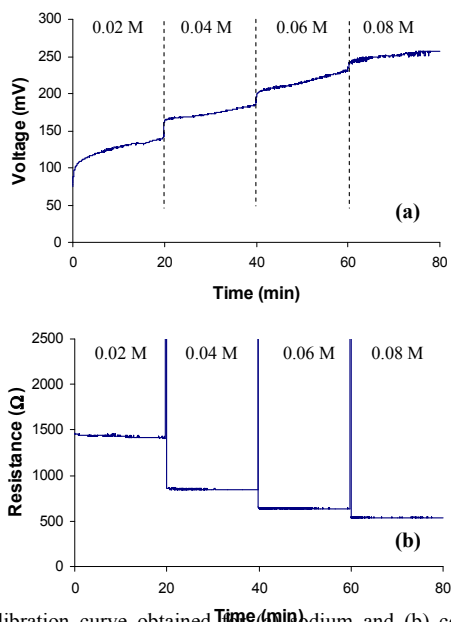


Fig. 8. Calibration curve obtained for (a) sodium and (b) conductivity sensors for concentrations of 0.02, 0.04, 0.06, 0.08 M Na^+

It can be seen from Fig. 8(a) that the solid contact sodium ISE displays a degree of upward drift. This phenomenon is well known where solid contact working and reference electrodes are used [17]. It can be attributed to inner phase boundaries which are not as well defined as those of classical ISEs, where inner filling solutions are used. Future work will involve efforts to eliminate this type of drift and on using these sensors in conjunction with the pH and

reference sodium sensor during on-body exercise trials.

IV. CONCLUSION

In this work, the design of a textile based fluid handling system has been outlined. It has also been demonstrated that this system provides a platform for the development of wearable biochemical sensors. In-vitro and in-vivo testing of pH, sodium and conductivity sensors has been completed. It can be seen that each sensor has the potential to be used for the real time analysis of sweat.

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